FIRST MEASUREMENTS OF NON-INTERCEPTIVE BEAM PROFILE MONITOR PROTOTYPES FOR MEDIUM TO HIGH CURRENT HADRON ACCELERATORS*

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Abstract

In the frame of the IFMIF-EVEDA [1] accelerator project (a 125 mA, 9 MeV, 175 MHz (CW) deuteron accelerator) CIEMAT has designed and tested two types of non-interceptive optical monitors based on gas fluorescence. This beam diagnostic technique offers a non-invasive beam profile characterization for medium to high current hadron beams. Both monitors have been tested at CNA cyclotron [2] using 9 MeV deuterons up to 40 μA and 18 MeV protons up to 10 μA. Profile measurements were carried out under high radiation background because the target and profilers were close to each other in the experimental setup.

In this paper, a brief description of fluorescence profile monitors (FPMs) together with the first beam measurements including systematic scans on beam current and pressure are presented.

INTRODUCTION

A high power beam (e.g. 1.125 MW for IFMIF-EVEDA) is potentially harmful for any interceptive diagnostic even though operated at low duty cycle. Hence, non-interceptive diagnostics needs development to be used during nominal operation of the accelerator.

A beam profiler based on the fluorescence of the residual gas in one of the best candidates due to its intrinsically high versatility. As a consequence of the beam particles passing through the vacuum pipe, the residual gas particles are excited. Photons are produced due to the de-excitation of the gas molecules or atoms of this residual or injected gas. The light emitted can be collected and used for the determination of the beam profiles without intercepting the beam. This technique has already been tested at high-energy proton and heavy ion accelerators [3-5].

Two fluorescence profile monitors prototypes have been designed and developed at CIEMAT and tested with beam for the first time at Centro Nacional de Aceleradores (CNA) in Sevilla. Both monitors are designed to be used under low level light environments being the image optical properties easily changed by means of a simple lens change.

Although the beam current during experiments was lower than IFMIF-EVEDA, the rest of parameters like energy, cross sections, branching ratios of transitions or efficiencies among others will be the same, with the exception of vacuum pressure. Since the number of photons produced during the beam-gas interaction increases linearly proportional with the beam current and pressure, an extrapolation to high current scenarios will be straightforward without having uncertainties in other parameters.

The objective of these tests is to demonstrate the capability of measuring deuteron profiles with closest conditions available to IFMIF-EVEDA ones.

FPM PROTOTYPE DESIGNS

Prototype FPMs developed are based on a custom intensified Charge Injection Device (CID) camera and on a Photo Multiplier Tube (PMT) linear array. A brief description of both prototypes can be found in next subsections.

Custom ICID Based Profiler

As standard commercial intensified cameras do not satisfy the detector requirements (like sensor reliability under radiation environments) a custom intensified camera has been developed. A Proxitronic image intensifier was coupled to a radiation hard CID camera model 8726DX6. The Proxitronic intensifier unit selected has a bialkali photocathode and a P46 phosphor screen with a quartz input window. The whole system is called intensified CID (ICID).

PMT Based Profiler

The second prototype is based on a linear multianode PMT coupled to a lens. The 32 channel PMT H7260 from Hamamatsu Photonics with a Bialkali photocathode and quartz input windows was selected. For the charge integrator and data acquisition a PhotoniQ IQSP482 from Vertilon Corp. was chosen. The PMT array is mounted in an interface board together with the lens objective in a custom design and compact assembly for a safe handling interface.

The movable interface board improves the operation of the lens by changing the minimum focusing distance of operation.

EXPERIMENTAL SETUP

The FPM prototypes were installed at the end of the experimental line of the cyclotron just upstream the rotating wire scanner (BPM-83 from NEC Corp.) in order to crosscheck the profiles acquired by the FPM. The beam was stopped at the end of the line with a faraday cup (FC) of aluminium plus a thin layer of graphite. Both FPMs

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were installed in horizontal position, looking at the Y projection of the beam at the same point.

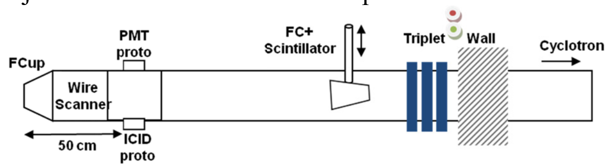


Figure 1: Layout of diagnostics installed at CNA experimental line. Green and red dots close to the wall represent gamma and neutron detectors.

After the installation of the diagnostics in the beam line, the ICID was calibrated by inserting a ruler pattern in the center of the beam pipe. Although profiles from wire scanner could be used for recalibration, it was by far preferable to calibrate the ICID system itself to make an independent cross-check between profilers, otherwise, some effects could be hidden (e.g. different physics principle or different locations). On the other hand, the PMT was calibrated using ICID prototype profiles but both profilers were installed one in front of each other, measuring both the same physics phenomena and hence minimizing experimental errors. A dedicated calibration pattern is presently being developed for the PMT device.

The ICID spatial calibration was performed in a low and non uniform light ambient scene. An Edmund Optics Megapixel *f*=25 mm lens was used and an *f*/2.8 was chosen. The maximum field of view (FOV) was 18.1±0.1 cm, being the total scale factor of the system for the y-axis β_y=0.055.

RECREATING HIGH CURRENT

The emissivity (ε) (Eq. 1) of the residual gas due to the interaction with beam ions, can be defined as the number of photons emitted per second for a given length path (d_{path}). It depends as well on the beam current **I**, the number of residual gas particles inside of the beam-gas interaction volume (pressure P_{gas}) and the total cross sections (σ). Hence, the number of photons measured (Eq.2) and more specifically, the final number of counts measured by a detector (N) depends on the emissivity, the solid angle (Ω), the integration of time (τ) and the total efficiency of the system (χ^{sist}).

$$\varepsilon \sim \sigma\, P_{gas}\, I_{beam}\, d_{path} \qquad (1)$$

$$N \sim \varepsilon\, \Omega\, \tau\, \chi^{sist} \qquad (2)$$

In order to extrapolate the results of the test to the IFMIF-EVEDA conditions, it is important to minimize the free parameters in order to get more reliable results. Test done with 9 MeV deuterons guarantees the same cross sections and branching rations of the line transitions than those present in IFMIF-EVEDA. Moreover, the efficiency of the systems, the equivalent length paths and the solid angles will keep constant (at least for the same design). The integration time is used for the extrapolation.

The emissivity and thus, the number of photons, can be increased linearly by changing the number of particles involved in the interaction, i.e. increasing the beam current or gas pressure. See Eqs. 1-2. Taking the advantage that the parameters will be the same in IFMIF-EVEDA except for the high current, the different conditions of IFMIF-EVEDA can be easily compensated at these tests by increasing the gas pressure. Thus, a straightforward extrapolation for a higher current deuteron beams can be made.

FIRST MEASUREMENTS WITH DEUTERONS

The FPM prototype based on PMT was able to measure deuteron profiles with lower beam currents than ICID prototype. Figure 2 shows a beam profile recorded using a 9 MeV deuteron beam with a particle current of 400 nA. Nitrogen gas (N_2) was injected up to reach a pressure of 3.6e-4 mbar inside the vacuum chamber. With those conditions a clear beam profile was measured having enough statistics for 100 ms of integration time and a 900 V for the PMT-voltage. A Gaussian fit was performed to the data. The estimated FWHM (within RMSE) was 2.4±0.1 cm. If the FWHM error is displayed within 95% of confidence interval, then the value is 2.4±0.3 cm, which guarantees a safer margin for a diagnostic which has not an in-situ calibration system designed. The errors can be minimized to match requirements by several ways. For example, the statistical errors could be reduced by changing the aperture of the lens, or the calibration errors could be minimized by using specific calibration pattern. Statistics will be improved as well when a more focused beam will be present because the higher density of photons. The resolution can be changed easily also by changing the lens.

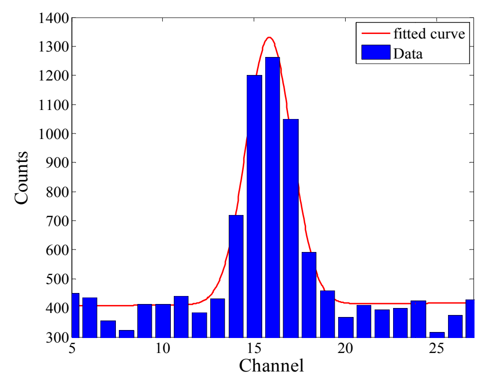


Figure 2: First profile acquired with the PMT_FPM prototype for a deuteron intensity of 400 nA and a N_2 pressure of 3.6e-4 mbar, together with a fit to the data.

Looking at the S/N ratio of the Fig. 2 data, a measurement of the profile at lower pressure or current can be also obtained. Unfortunately, measurements at lower current were not performed and data in Fig. 2 was recorded with the lowest current and pressure combination during CNA experiments. Hence, taking into account the size of the beam, probably these are not the minimum beam conditions required to measure a profile.

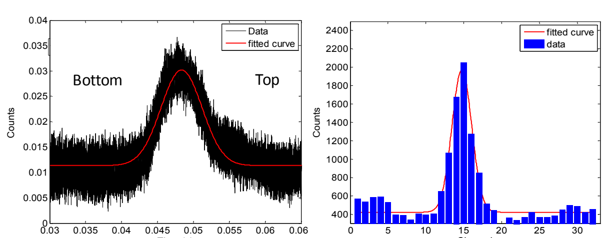
Minimum Beam Pulse

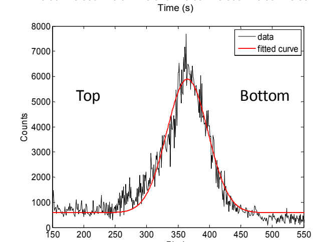
Using the previous data, the minimum pulse requirements for a 9 MeV deuteron beam with a current of 125 mA to measure a similar profile can be estimated. If the product between the beam current, the pressure and the acquisition time (or beam pulse) is kept constant, a similar profile should be able to be measured. In fact, this product is for the parameters of the experiment: 4e-4 mA x 3.6e-4 mbar x 100 ms=1.44e-5 [mA mbar ms]. Comparing this value to the IFMIF-EVEDA case that is 125 mA x 1e-6 mbar x t_{pulse}, a beam with a single pulse (t_{pulse}) of 115 µs which corresponds to a 0.01% of duty cycle could be measured. For those calculations, a pressure of 1e-6 mbar has been taken as reference although any pressure could be used (e.g. for 1e-7 mbar an equivalent ~1.2 ms pulse length is obtained). For the monitors located at the end of the IFMIF-EVEDA line (pressure of 1e-5 mbar in nominal conditions), it will be equivalent to a beam length pulse of 11.5 µs.

Preliminary Cross Check between Profilers

Beam profiles measured with the PMT, the ICID and a wire scanner for a 15 µA deuteron beam with a N_2 pressure of 7e-4 mbar are shown in Fig. 3. The profile measured with the wire scanner is shown for comparison purposes. A small deviation is observed systematically in the top side view of the beam pipe for the different monitors.

The voltage applied to ICID and PMT plates were 1580V and 900 V respectively, whereas integration times were 20 ms and 5 ms. A 1.7 ms beam pulse for the ICID (Fig. 3 left bottom) and a 420 µs pulse for the PMT (Fig. 3 right-top) will be needed to replicate similar profiles for IFMIF-EVEDA with these detector settings.





Profiler	FWHM (95% C.I.)
Wire Scanner	2.44±0.03 cm
PMT	2.4±0.3 cm
ICID	2.42±0.07 cm

Figure 3: Deuteron beam profiles recorded by a wire scanner (left-top), PMT profiler (right-top) and ICID profiler (left-bottom) are shown together with Gaussian fits.

The measured profile systematically shows a small deviation in the top side of the beam pipe and is registered by the different profilers. The profile shapes recorded by all the profilers are in good agreement between them for these preliminary tests. No profile asymmetries deformations or tails are noticed between profilers.

During these profile measurements, the radiation monitors measured ~27.2 mSv/h dose rates for gammas and ~6.5 mSv/h for neutrons as discussed in a subsequent section.

CURRENT AND PRESSURE SCANS

In order to check the linear relation of the profile intensity with the beam current and gas pressure as well as to check the reproducibility and reliability of the fluorescence technique, two types of scans were performed. For these tests, only one parameter was changed (current or pressure), being all the other experimental and instrumental parameters fixed.

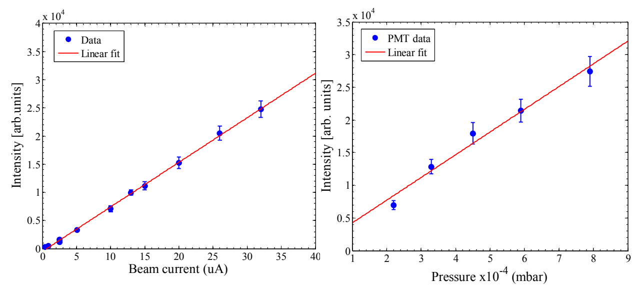


Figure 4: Profile intensities versus current scan (left) and pressure scan (right) for the PMT prototype.

For the current scan the vacuum pressure was fixed at 2.3e-4 mbar whereas for the pressure scan the beam current was fixed at 10 µA.

The linear relation expected between the number of counts and beam current or the vacuum pressure was confirmed experimentally (see Fig. 4). The profile FWHMs remain constant (within error bars) for both current and pressure scans.

Xenon Gas

A second current scan was performed using Xenon (instead of N_2) as residual gas with a constant pressure of 8.6e-4 mbar. The behaviour of the profile intensities and background levels compared with those recorded for N_2 are shown in Fig. 5. As pressures are different, only a relative comparison can be done. It is apparent that the intensity and background levels increases linearly with the beam current, but some features can be highlighted. The profile intensities recorded using N_2 (see Fig. 5 top) are 400% higher than those recorded using Xe, even when the Xe pressure was higher. The photon yield, at least in the range of 380-650 nm spectral efficiency of the detector, is clearly higher for nitrogen than for xenon. Similar tendencies have been reported previously using different beam ion species [6-7].

Background during Measurements

As shown in Fig. 5, background levels and intensities do not follow the same relative tendencies between N_2 and Xe gases. Contrary to intensities, the background slopes remains constant for both gases within the error bars (22% higher for N_2 without error bars). Hence, the major contributor to background level is expected to be the radiation, instead of reflected or scattered photons in the visible region. Radiation background for a fixed beam current is constant independently of the residual gas used (under such pressures) whereas increases linearly with the beam current.

Usually beam profilers are outside the shielded target area. In this case, the beam profilers and the faraday cup (target) were in the same vault (Fig. 1) so they had to deal with an important radiation background.

Beam profiles shown in Fig. 3 were recorded under 27.2 mSv/h gamma doses. The FPM prototypes were capable to measure profiles with good S/N ratios with such gamma background, being the PMT prototype less affected than ICID. Although radiation increases the background noise in detectors, it seems that the FPMs could operate even without any shield under those radiation doses (the performance of detectors will not be severely limited). Nevertheless a custom design shield will improve the measurements and the operational life of the system.

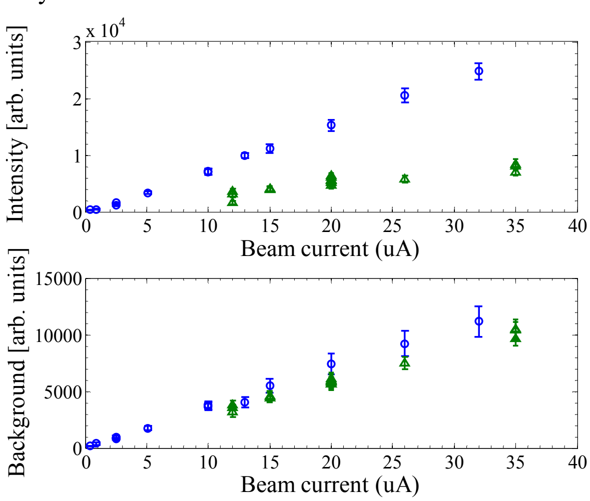


Figure 5: Profile intensities (top) and background levels (bottom) using nitrogen (circles) and xenon (triangles) as residual gas plotted versus the beam current.

The systematic analysis of different scans shown in this paper was done using PMT-prototype data only. The amplification of the ICID-prototype had to change during the experiments because of image saturation. It seems that ICID is more sensitive to background radiation than the PMT based prototype.

In the case of high current and medium energy (tens of MeV) enough statistics are expected for profile measurements with such monitors. Due to the expected good statistics, a mirror system can be used to minimize background and instrumentation damage for those profilers installed close to a target.

MEASUREMENTS WITH PROTONS

Beam profiles for 18 MeV protons have been measured with the PMT prototype (Fig. 6). A beam current of 10 μA, a gas pressure of 3.2e-4 mbar and 50 ms of integration time was required to obtain a similar profile as shown in Fig. 3 right-top. If the products of beam current, pressure and acquisition time for both examples are compared, a factor 3 is obtained. Hence, this is the factor needed to match similar conditions between 9 MeV deuterons and 18 MeV protons (equivalent to 36 MeV deuterons).

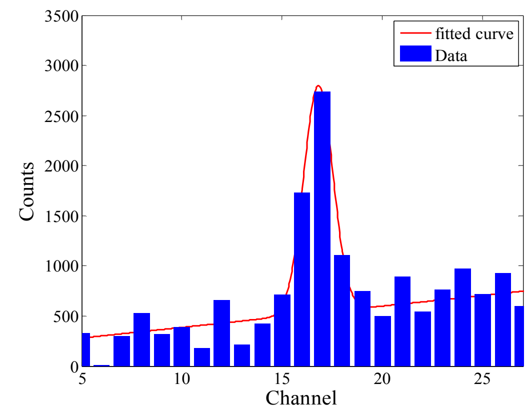


Figure 6: Beam profile for 18 MeV and 10 μA proton beam with a vacuum pressure of 3.2e-4 mbar. Profile background was removed for comparison purposes.

CONCLUSIONS

Two prototypes of non-interceptive profile monitors based on residual gas fluorescence have been designed for the IFMIF/EVEDA accelerator. First tests with beam have been carried out successfully at CNA cyclotron with deuteron and proton beams. Measurements under different experimental conditions were performed and the tendencies have been highlighted. Systematic scans on beam current and gas pressure shows the consistency and reliability of this beam profile technique. The gamma and neutron background contribution to the measured background level on the detector is presently under analysis. As a work in progress, there will be some improvements in the near future as a blackened vacuum chamber or a dedicated calibration pattern.

REFERENCES

[1] P. Garin et al., EPAC'08, TUZG01, (2008).
[2] Centro Nacional de Aceleradores; http://intra.sav.us.es:8080/cna/index.php/en.
[3] M.Plum. et al., Nucl. Instr. and Methods Phys. Res. A 492 (2002) 74-90.
[4] P. Forck et al., DIPAC'05, ITTA01, (2005).
[5] T. Tsang et al., Rev. Sci. Instrum. 79, 105103 (2008).
[6] C. Böhme et al., DIPAC'09, TUPB10 (2009).
[7] F. Becker et al., DIPAC'09, TUPB02 (2009).